HIGH VOLTAGE POWER CONDITION SYSTEMS
POWERED BY FLUX COMPRESSION GENERATORS*

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Abstract

Compact, high-gain magnetic flux compressors (FCGs) are convenient sources of substantial energy for plasma-physics and electron-beam-physics experiments, but the need for high-voltage, fast-rising pulses is difficult to meet directly with conventional generators. While a variety of novel concepts employing simultaneous, axially-detonated explosive systems are under development, power-conditioning systems based on fuse opening switches and high-voltage transformers constitute an approach that complements the fundamental size, weight, and configuration of small helical flux compressors. In this paper, we consider, first, a basic inductive store/opening switch circuit and the implications associated with, specifically, a fuse opening switch and an FCG energy source. We develop a general solution to a transformer/opening switch circuit — which also includes (as a special case) the direct inductive store/opening switch circuit (without transformer) and we report results of one elementary experiment demonstrating the feasibility of the approach.

Basic Opening Switch Circuit

We recall the fundamental behavior of a current interrupting switch, limiting our consideration to the case where the load is switched across the opening switch and storage inductor at the time when the voltage across the opening switch reaches a peak. Thus, the behavior of the circuit up to the time of peak voltage is independent of the load. For purposes of analysis we consider a switch whose resistance rises linearly from $R = 0$ at $t = t_c$ in Fig. 1, thus

$$R_{(t)} = \dot{R}t' \quad ,$$

where we use primed time coordinates to measure time from the end of the "conduction time," t_c, $(t' = t - t_c)$. The circuit equation for the circuit in Fig. 1, before the output switch closes is:

$$L(dI/dt) + IR_{(t)} = 0$$

and the solution is:

$$I_{(t')} = I_o e^{-\dot{R}t'^2/2L} \tag{1}$$

where I_o is the current in L before the start of interruption.

It is convenient to identify a "switching interval," t'_{sw}, during which the current has been virtually interrupted, falling to $I(t'_{sw}) = I_o e^{-2}$ (14% I_o), and from Eq. (1) we identify

$$t'_{sw} = 2\sqrt{L/\dot{R}} \quad .$$

Furthermore, we can write the voltage across the switch

$$V_{(t')} = R_{(t')}I_{(t')} = \dot{R}I_o t' e^{-\dot{R}t'^2/2L} \quad .$$

We can find the time, t'_{vm}, of maximum voltage by taking $\partial V/\partial t = 0$.

$$t'_{vm} = \sqrt{L/\dot{R}} = 0.5\ t'_{sw}$$

and at t'_{vm} the current is

$$I_{(t'_{vm})} = I_{vm} = I_o e^{-1/2} \quad (61\%\ I_o)$$

which is a consequence of assuming a linear rise in the switch resistance. At t'_{vm} the resistance and voltage are:

$$R_{(t'_{vm})} = \sqrt{\dot{R}L} = 2\ L/t'_{sw} \quad .$$

$$V_{(t'_{vm})} = 1.2\ LI_o/2\sqrt{L/\dot{R}} = 1.2\ \Phi_o/t'_{sw}$$

where $\Phi_o = LI_o$ is the flux in L prior to the start of interruption. The energy dissipated in the switch up to the time t'_{vm} is

$$E_{min}(t'_{vm}) = 0.5\ L(I_o^2 - e^{-1}I_o^2) = 0.63\ E_o \tag{2}$$

where E_o is the energy in the circuit at t_c. We see that E_{min}, which is the minimum energy that any switch displaying a linear resistance profile must dissipate, is independent of the details of the switching mechanism and of the circuit parameters.
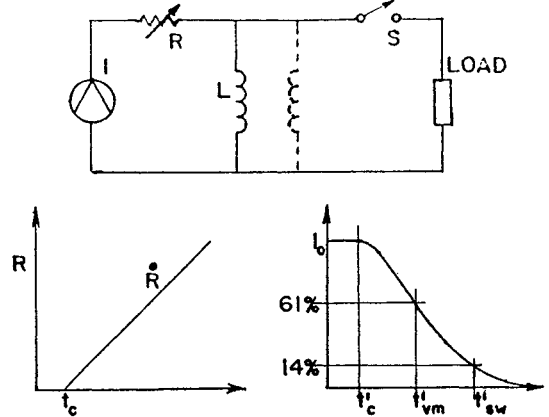

Fig. 1. Basic opening switch circuit with ramp resistance.

When the switching mechanism is, more specifically, a fuse, we follow convention (which is well supported by more than 20 years of experiments conducted worldwide) and assume that the fuse begins to vaporize and begins its large increase in resistance at t_v when the accumulated specific action reaches a value determined only by the nature of the material.[1,2]

$$\frac{1}{A^2}\int_0^{t_v} I(t)^2 dt = g_o \tag{3}$$

where g_o is the "burst" specific action and A is the cross section of conductor presented to the current. Since different current waveforms deliver action to the fuse in dramatically different ways (e.g., capacitor bank compared to flux compressor waveforms), it is useful to introduce an "equivalent action time scale" τ_{eq}.

$$\tau_{eq} = 1/I_{(t)}^2 \int_0^t I(t)^2 dt \tag{4}$$

Thus, using Eqs. (3) and (4) we establish a criterion for the area that the fuse must be presented to the current in order to achieve the beginning of vaporization at $t_v = t_c, I(t_v) = I_o$

$$g_o A^2 = I_o^2 \tau_{eq}$$

$$A = I_o(\tau_{eq}/g_o)^{1/2} = k_1 I_o \tau_{eq}^{1/2} \quad . \tag{5}$$

Because a switch (displaying a linear resistance increase) must dissipate energy, ΔE, which lies between E_{min} and the total circuit energy E_o

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$$\Delta E = \alpha E_o \quad , \quad 0.63 \le \alpha \le 1.0 \tag{6}$$

a criterion on the fuse length, l, is defined by the requirement to bring the fuse of mass $(\rho l A)$ to burst energy density ε_b using only a total energy ΔE.

$$\Delta E = \varepsilon_b \rho l A = \alpha E_o$$

Using Eqs. (2), (5), and (6):

$$l_o = \frac{\Delta E}{\varepsilon_b \rho A} = \alpha \frac{\frac{1}{2} g^{1/2}}{\varepsilon_b \rho} \frac{\Phi_o}{\tau_{eq^{1/2}}} = \alpha k_2 \Phi_o \tau_{eq}^{-1/2} \quad . \tag{7}$$

Using Eqs. (5) and (7) we arrive at the initial resistance of the fuse:

$$R_o = \alpha \eta_o \frac{k_2}{k_1} \frac{\Phi_0}{I_0} \frac{1}{\tau_{eq}} = \alpha \eta_o \frac{k_2}{k_1} \frac{L}{\tau_{eq}}$$

where η_o is the initial resistivity of the fuse material. During vaporization, between t_c' and t_{vm}', we assume that the resistance of the fuse rises (linearly) by a ratio M_f. This approach combines all the details of EOS, hydrodynamics, tamping and quenching into the parameter M_f, and a first principles computational model is being developed to estimate M_f.[3] Thus, the fuse resistance at t_{vm}' is $R_{vm} = M_f R_o$, but from circuit considerations we recall $R_{vm} = 2L/t_{sw}$, therefore,

$$R_{vm} = M_f \alpha \, \eta_o k_2 L / k_1 \tau_{eq} = 2L/t_{sw}'$$

which provides an expression for the switching speed of the fuse

$$t_{sw}' = \frac{2k_1}{\alpha \eta_o k_2} \frac{\tau_{eq}}{M_f} = \frac{1}{\alpha} k_o \frac{\tau_{eq}}{M_f} \tag{8}$$

and finally the voltage and electric field produced by the fuse are:

$$V_m = \frac{1.2 \, \alpha \, M_f \Phi_o}{k_o \tau_{eq}}$$

$$E_m = k_3 \frac{M_f}{\tau_{eq}^{1/2}} \quad .$$

Equation (8) provides an expression for the current interruption time in terms of material parameters, k_o, the resistance multiplication ratio and the parameter τ_{eq}. Material parameters for copper and aluminum are summarized in Table I using Tucker, Toth information and material properties are assumed to be independent of circuit or source parameters. Thus, the parameters that can effect the current interruption time are the equivalent action timescale and the multiplication. Equation (4) for τ_{eq} can be evaluated analytically for the case of a sinusoidal current waveform (such as a capacitor bank) and for an exponential current waveform (which approximates the waveform of most flux compressors). For a sinusoidal waveform with a quarter period τ_q we find $\tau_{eq} = \tau_q/2$. While for an exponential waveform $I_{(t)} = I_o e^{\gamma t/t_r}$ where γ is the exponential factor and τ_r is the full operating time (run time) of the generator, we find $\tau_{eq} = \tau_r/2\gamma$. The τ_r of flux compressors can vary from 10 μs to several hundred microseconds, and the exponential factor from 1 to about 5. We calculate the action timescale from experimental waveforms of three flux compressors in Fig. 2. All are helical flux compressors with the explosive charge initiated at one end. The first is a relatively compact high current-gain configuration, the second is a similar small generator consisting of a helical section and a coaxia section designed to produce larger currents and the third is a very large (relatively slow) generator designed to produce very large energies. The curves show similar general behavior and all contain a relative minimum in τ_{eq} near the end of the run but not necessarily at peak current. For minimum current interruption time Eq. (8) shows that a fuse should be designed to burst at this minimum in the τ_{eq} profile assuming that M_f is not a function of τ_{eq}.

Table I.

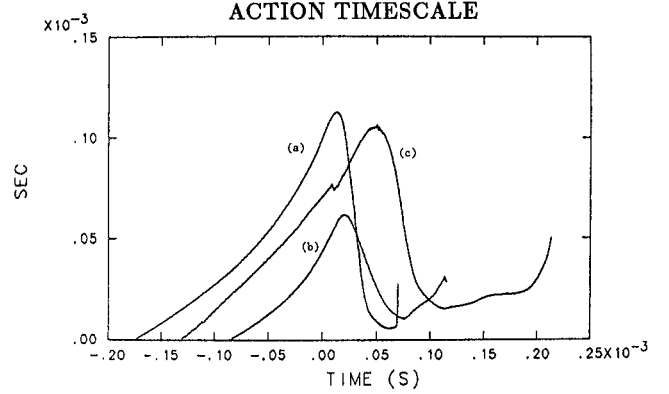|		Aluminum	Copper
k_o	$4\rho \varepsilon_b / \eta g_o$	77	94
k_1	$g_o^{-1/2}$	4.5×10^{-9}	2.8×10^{-9}
k_2	$\frac{0.50 g_o^{1/2}}{\varepsilon_b \rho}$	4.2×10^{-3}	3.3×10^{-3}
k_3	$0.6 \eta g^{1/2}$	3.7	3.8

Fig. 2. Action time scale for three FCGs.

Circuit Analysis

With this general description of fuse opening switch performance, we next explore two circuit concepts outlined in Fig. 1. In one, the energy is stored in the primary inductance of a transformer and released by an opening switch, and in the other, the transformer degenerates into a simple storage inductor. We first develop the general solution for an energy storage transformer with an opening switch in the primary loop and a resistive load in the secondary loop. The general circuit is shown in Fig. 3a where $L_g(t)$ is the variable inductance of a flux compression generator, $R_s(t)$ is the resistance of the opening switch in the primary loop, L_{xp} is the total inductance in the primary loop that is "external" to both the generator and the transformer, and L_p is the primary inductance of the transformer. Similarly, L_s is the secondary inductance, L_{xs} is the inductance in the secondary loop external to the transformer (including the inductance of the load) and R_L is the load impedance. M is the mutual inductance coupling L_p and L_s.
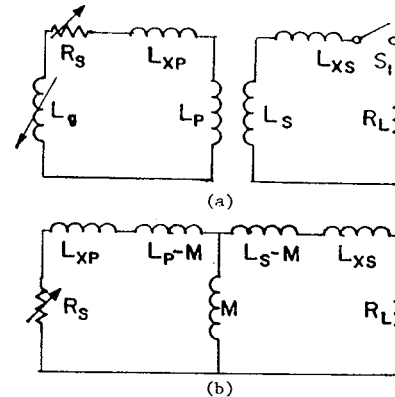

Fig. 3. Transformer circuit (a), equivalent circuit (b).

When the generator completes its operation, $L_g(t)$ approaches zero, and by replacing the transformer with the familiar "T Equivalent" we describe the circuit as shown in Fig. 3b at the instant just prior to current interruption. The transformer is described by the physical quantities L_p, L_s, and M, Following convention, we define the coupling, k, and the quantity N, which we associate with the physical turns ratio in simple geometries,

$$k = M/\sqrt{L_p L_s} \qquad N = \sqrt{L_s/L_p} \quad .$$

For convenience, we rewrite the circuit in Fig. 3b by combining inductances in the primary and secondary loops and arrive at the circuit in Fig. 4 where we define:

$$L_1 = L_{xp} + L_p \qquad L_2 = L'_{xs} + L_s$$

$$k_{eq} = M/\sqrt{L_1 L_2} \le k \qquad N_{eq} = \sqrt{L_2/L_1} \quad .$$

So that the effect of external inductances is included in k_{eq} and N_{eq} — reducing the coupling and making N_{eq} possibly quite different from the physical turns ratio.

At this point, we observe that the circuit in Fig. 4 can also be used to describe the transformerless approach by setting $L_p = L_s = M = L_{\text{store}}$. Then

$$L_1 = L_{xp} + L_{\text{store}} \qquad L_2 = L_{xs} + L_{\text{store}}$$

and for $L_{xp}, L_{xs} = 0$
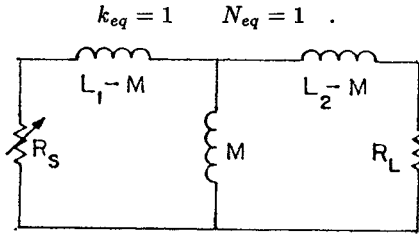
$$k_{eq} = 1 \qquad N_{eq} = 1 \quad .$$

Fig. 4. Circuit for general solution.

For analysis, we define the switching action as an instantaneous transition in R_s from $R_s(t^-_{vm}) = 0$ to $R_s(t^+_{vm}) = R_s$. The transition occurs at $t = t_{vm}$. And at $t^+_{vm}, I_{(t)}$ has fallen to I_{vm}. This allows a general solution of the circuit equations to be written as:

$$I_2 = I_p e^{-t/\tau_f}\left(1 - e^{-t/\tau_r}\right)$$

where:

$$I_p = I_{vm} k_{eq}/N_{eq}(1 + r)Q \quad , \quad I_{vm} = 61\% \, I_o$$

$$\tau_r = \tau_x(1 - k^2)/2Q$$

$$\tau_f = \tau_x(1 - k^2)/(1 - Q)$$

where r is the dimensionless ratio of load resistance to switch resistance scaled by the equivalent turns ratio N_{eq}, and τ_x is a characteristic time scale.

$$r = R_L/R_s N^2_{eq}$$

$$\tau_x = 2L_2/(R_L + N^2_{eq}R_s)$$

$$Q = \sqrt{1 - 4r(1 - k^2)/(1 + r)^2} \quad .$$

We observe that for good coupling, $k \to 1$, $Q \to 1$, independent of r. Thus, the ratio of the rise time to the fall time of the secondary current

$$\tau_r/\tau_f \simeq (1 - Q)/2Q \Rightarrow 0$$

and the output current has a risetime much less than the fall time. And we can treat I_p as the peak value.

Furthermore, we observe that for $r = 1$, $Q \to k$ and

$$I_p \to 0.5 I_{vm}/N_{eq} \quad .$$

Figure 5 shows the magnitude of current in the secondary loop (normalized to I_{vm}/N_{eq}) as a function of r with k as a parameter. The figure shows that for small r, $I_p \to k I_{vm}/N_{eq}$; and for large r, $I_p \to k I_{vm}/r N_{eq}$.
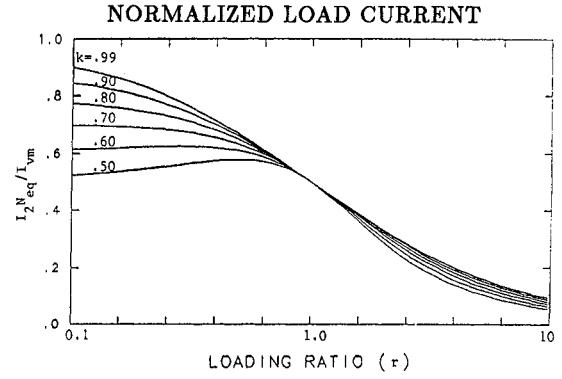
NORMALIZED LOAD CURRENT

Fig. 5. Normalized circuit in secondary loop.

Figure 6 shows the values of the rising (τ_r) and the falling (τ_f) time constants, normalized to τ_x, as functions of r with k as a parameter. The figure shows that τ_r peaks at $r = 1$ (but not sharply) and that τ_f has a minimum a $r = 1$. τ_r approaches zero (a step rise in current) independent of r for $k \to 1$.
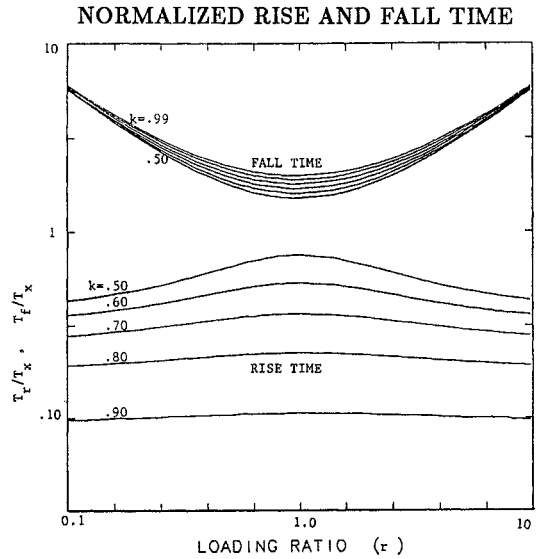
NORMALIZED RISE AND FALL TIME

Fig. 6. Normalized time constants.

From the solution, we can also write the voltage across R_L:

$$V_{lp} = R_L I_p = I_{vm} k R_L N_{eq}/Q(N^2_{eq} + R_L/R_s) \quad .$$

Figure 7 shows $V_{lp}/R_s N_{eq} I_{vm}$ as a function of r with k as parameter.

Frequently, we would like to choose the transformer design to maximize the voltage impressed across a load assuming a given performance for the opening switch. We find the value of N_{eq} for which V_{lp} is a maximum by finding where $\partial V_{lp}/\partial N_{eq} = 0$. For case of relatively good coupling $1/Q \to 1$, we find that the maximum occurs where

$$R_L = N^2_{eq}R_s \quad , \quad (\text{i.e., for } r = 1) \quad .$$

Furthermore when $r = 1$, we see that $Q = k$ and the voltage across the load and power to the load are:

$$V_{lp} = \frac{1}{2}\frac{I_{vm}R_L}{N_{eq}}$$
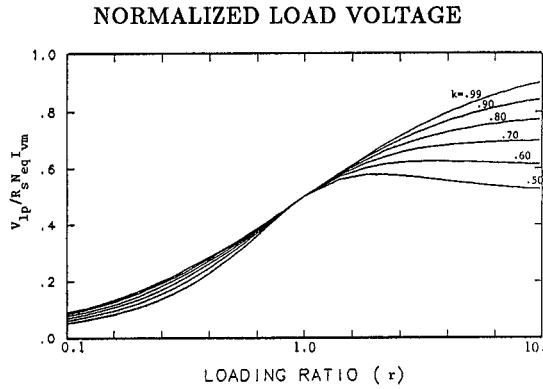
$$P_{lp} = \frac{1}{4}R_s I^2_{vm} \quad .$$

973

NORMALIZED LOAD VOLTAGE

Fig. 7. Normalized load voltage.

TRANSFORMER EXPERIMENT

Fig. 9. Simple transformer experiment.

Performance Estimates

As an example of applying the results of the previous sections to a flux compression generator power-conditioning system, we consider a 50-μH flux compressor operating into a 500-nH storage inductor (L_{store}) with a series current interrupting fuse. We explore first the performance to be expected for a 10-Ω load coupled across the fuse at the time of peak voltage. We then explore the improvement in performance to be expected by introducing an optimized transformer with a 500-nH primary inductance.

For illustrative purposes we consider the flux compressor to be initially loaded with 20-kA current, resulting in 1.0 Weber initial flux. We assume 50% flux efficiency, $\tau_r = 100$-μsec, $\gamma = 5$ and $\tau_{eq} = 10$-μsec, resulting in a current of 1 MA in the storage inductor and 610 KA at t'_{vm}. For the switch, we assume aluminum conductor, a multiplication of $M = 300$, and we find $R_{vm} = 333$ mΩ.

For a direct store/switch configuration in coaxial geometry with the load coupled across the fuse we take $L_{xp} = 0, L_{xs} = 25$ nH, $R_L = 10$ Ω. Thus, with $L_s = L_p = 500$ nH, we find $k_{eq} = 0.98$, $N_{eq} = 1.025$, and $r = 28.6$, which results in $V_{lp} = 197$ KV, $\tau_r = 2.4$ ns, and $\tau_f = 1.6$ μs.

According to this analysis, N_{eq} should be selected to achieve $r = 1$, i.e., $N_{eq} = 5.5$. For the assumed generator and switch performance, $L_s = 15.13$ μH, M = 2.20 μH and $k = 0.8$ we find $V_{lp} = 556$ KV, $\tau_r = 337$ ns, and $\tau_f = 2.7$ μs.

In Fig. 8 we plot the voltage predicted across 4, 10, and 25-ohm loads for the representative flux compressor and fuse as a function of the physical turn ratio N with $k = 0.8$. For each case we mark $r = 1$ and observe that a 4-Ω load experiences a peak voltage of 350 KV and the power to all loads is about 30 GW.
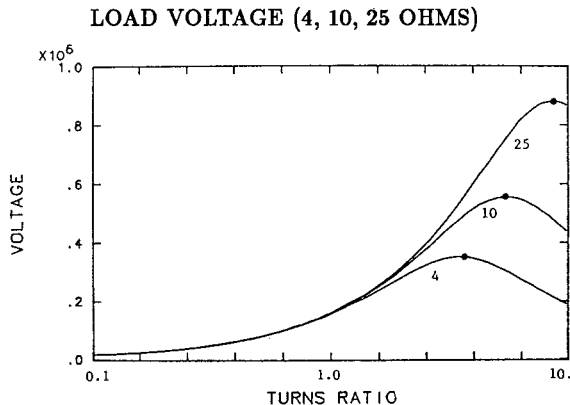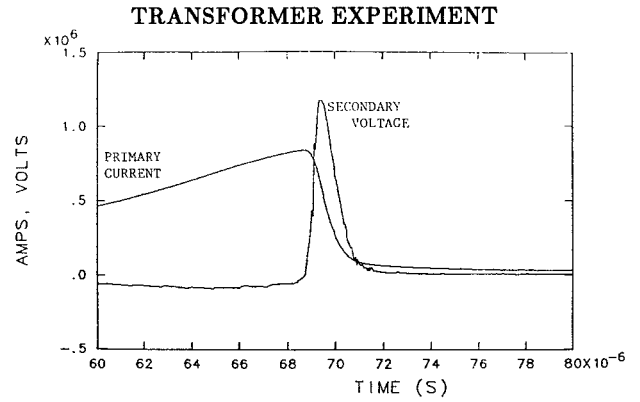
Experiment

To demonstrate the feasibility of a flux compressor, fuse, and transformer power-conditioning system, a 0.5-MJ class flux compressor was operated into the primary of a rudimentary (non-optimized) transformer coupled to a 60-kΩ load. The generator initial inductance was 50 μH, and the initial current was about 25 kA. The copper fuse was 40-cm long, 52-cm wide, and 0.35-mil thick. The fuse material was bonded between two layers of 0.010 Mylar making the package self supporting. The fuse was mounted coaxially with the small helical flux compressor. The helical transformer consisted of a 1.5-turn primary of about 270-nH and a 10-turn secondary, coupled with a $k = 0.70$. The load was a high-resistance liquid resistor of about 60 kΩ in series with the secondary without a series isolation switch. As shown in Fig. 9, the current in the transformer primary rose to about 800 kA and was interrupted in about 3 μs. The voltage in the transformer secondary, was about 1.3 MV.

Conclusions

Simplified analytic analysis shows that for powering resistive loads with an FCG/Fuse combination and a transformer, the turns ratio should be selected to match fuse to load impedances ($r = 1$). Under this condition, the current in and voltage across the load become independent of the transformer coupling but the rise and fall times are not. Using representative small flux compressors, fuses and matched transformers, loads at a few ohms can be driven to a few-hundred KV and loads of a few 10's of ohms can be driven to about 1 MV. Direct fuse power conditioners can be useful for voltages up to 300–500 KV but transformers are required for higher voltages.

References

[1] T. J. Tucker and R. P. Toth, "EBW1: A Computer Code for the Prediction of the Behavior of Electrical Circuits," SAND-75-0041, 1975.

[2] H. Knoepfel, Pulsed High Magnetic Fields, North-Holland, 1970, pp. 73–104.

[3] I. Lindemuth, J. Brownell, A. Greene, G. Nickel, T. Oliphant and D. Weiss, "A Computational Model of Exploding Metallic Fuses for Multimegajoule Switching," J. Appl. Phys., 57, 4447, 1985.

LOAD VOLTAGE (4, 10, 25 OHMS)

Fig. 8. Peak load voltage to representative FCG.